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13. ABSTRACT *(Maximum 200 words)*
The tropical marine fishes of the family Ostraciidae (boxfishes, trunkfishes, cowfishes) are the best available living models for engineered autonomous underwater vehicles (AUVs). The forward 2/3-3/4 of their bodies are encased in rigid bony carapaces that prevent their bending any parts of their bodies except the bases of their tails. As a result they swim entirely by means of movements of their five fins. We have studied four different species, each having a carapace of a different shape and structure. Field and laboratory studies show that they are all surprisingly fast and maneuverable, with considerable endurance. They swim through turbulent environments with excellent control and dynamic stability. They do this by using a series of different gaits (different patterns of coordinated and controlled fin movements). Two important results of their use of gaits are that: 1) they produce dynamic stability by continuously balancing turning force moments generated by the movements of their fins; and 2) they control the energy costs of swimming to unusually large extents. The morphological details of the structures of their carapaces are also important in producing these results. Flow visualization studies show that the carapaces generate vortical flows in specific locations.

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FINAL REPORT

GRANT #: N00014-96-1-0607
PRINCIPAL INVESTIGATOR: Malcolm S. Gordon
INSTITUTION: University of California, Los Angeles (UCLA)
GRANT TITLE: Biomechanics and Energetics of Locomotion in Rigid-bodied Fishes
AWARD PERIOD: 1 March 1996 - 31 December 2001

OBJECTIVE: To study the ways in which the rigid-bodied tropical marine armored fishes of the family Ostraciidae (boxfishes, trunkfishes, cowfishes) swim; to provide detailed databases on swimming mechanisms in these fishes (biomechanics, kinematics, kinetics, hydrodynamics) that can be used in the development of biomimetic (bioinspired) autonomous underwater vehicles (AUVs); to estimate energetic costs of swimming in these fishes.

APPROACH: The project had four major parts:

1) Use high-speed video and computerized motion analysis to describe the biomechanics, kinematics, and kinetics of body and fin movements in one species of boxfish swimming straight ahead over its full range of speeds.
2) Combine these datasets to produce a working hypothesis to account for the unusual properties of swimming in this fish, especially its ability to maintain dynamic stability while in turbulent environments.
3) Study the hydrodynamic properties of the differently shaped carapaces of four species of these fishes and determine the contributions made by the carapaces to their dynamic stability.
4) Estimate metabolic costs of swimming in one boxfish species by studying rates of oxygen consumption during swimming at different speeds, also compare those costs with swimming costs in a "standard" bony fish that lives in the same general environment as the boxfish.

ACCOMPLISHMENTS: We have essentially completed work on three of the four parts of the project, and are writing up the results from the fourth. Data obtained in all parts are complex and detailed. This report summarizes only the principal findings.

1) The spotted boxfish swims with surprising speed, endurance, maneuverability, and dynamic stability. It is a neutrally buoyant, multipropulsor AUV, using its five fins (two pectorals, dorsal, anal, and caudal fin) in precisely synchronized and coordinated ways to produce four gaits that are used over different ranges of speed. Swimming movements are unusually well controlled and smooth, showing substantially smaller recoil instabilities (pitch, yaw,

roll, heave, surge, and sideslip) than occur in almost all other fishes, both body and caudal fin (BCF) and median and paired fin (MPF) swimmers. This is true despite the facts that the different fins have different patterns of movements and are placed at different distances and in different directions from the center of mass of the body. Carapace shape plays several roles in swimming dynamics. The carapace is approximately trapezoidal in cross-section, with keels of varying sharpness at the corners. The keels are important generators of vorticity in the water flowing past them. This vorticity is a major contributor to the dynamic stability of swimming (see part 3).

2) The full set of results from part (1) permitted the development of a working hypothesis that is a quasi-mathematical model of the forces generated by and exerted upon a swimming boxfish. In broadest outline this model predicts that the small amplitudes of recoil movements shown by the fish while it is swimming in all but the burst and coast (highest speed) gait are primarily due to near exact, instantaneous, continuous balancing of the turning moments generated by each of the four active fins around the center of mass. Relaxing that balance in different ways, to different extents, at different times is what produces the maneuverability of the fish.

3) This part of the project used the results from the first two parts to guide a detailed engineering-style study of the hydrodynamic properties of the carapaces of the four major different body types occurring in ostraciid fishes. We made computer-assisted tomography (CAT) images of the bodies of single, carefully selected, typical specimens of the spotted boxfish, smooth trunkfish, buffalo trunkfish, and scrawled cowfish. Carapace cross-sectional shapes vary substantially between these species. The outputs of the CAT scans were used to produce dimensionally exact rapid prototyped epoxy models of each specimen. These models were then placed, as was appropriate for the study being done, in the working sections of either precision wind or water tunnels. Detailed, precise measurements were made of fluid flows around the models (DPIV studies), pressure distributions over the surfaces of the models, and mechanical forces generated by fluid flows. Models were positioned at varying angles of attack for both pitching and yawing modes. The major finding was that the keels in all body shapes are generators of strong longitudinal vortices that vary in strength and position with angle of attack. These vortices automatically contribute to generation of forces that correct for pitching or yawing

movements. Thus, essentially all morphological features of the carapaces of these fishes play significant roles in producing the dynamic stability shown by these animals.

4) We sought to determine the extent to which the unique swimming mechanisms used by boxfish have metabolic implications with respect to energy costs of swimming. We measured oxygen consumption rates in spotted boxfish swimming at different speeds in a water tunnel, at constant temperature. We also made comparable measurements on milkfish, a streamlined BCF swimmer, under the same conditions. The direct metabolic costs of swimming turned out to be the same in both species, which is surprising given the different swimming modes and different body shapes. The total costs of transport were quite different, however, a result we interpret as being a consequence of the use of swimming gaits by the boxfish, but not by the milkfish.

CONCLUSIONS: Ostraciid fishes are highly evolved sophisticated natural AUVs. They swim using a complex assortment of previously unknown mechanisms. A major result of the work is that we can account for a large part of the physical basis for the unusual dynamic stability shown by these animals while they swim in turbulent environments.

SIGNIFICANCE: We have shown that it is possible to quantitatively study swimming mechanisms in selected fishes using an array of engineering and analytical techniques. The results will be of interest to designers of human-made AUVs, as well as to basic scientists interested in animal locomotion, hydrodynamics, and aerodynamics.

PATENT INFORMATION: To date no patentable ideas or devices have resulted from this work.

AWARD INFORMATION: The PI was the Irving-Scholander Memorial Lecturer, University of Alaska - Fairbanks, in 2000. He was promoted to distinguished professor rank at UCLA.

PUBLICATIONS AND ABSTRACTS:

Refereed articles:

1. Gordon, M.S., J.R. Hove, P.W. Webb, and D. Weihs. (2000) Boxfishes as unusually well controlled autonomous underwater vehicles. Physiol. Biochem. Zoology 73: 663-671.

2. Gordon, M.S. and I.K. Bartol. (2000) Dynamic stability of swimming in boxfishes (Teleostei: Ostraciidae). Proc. 1st Intl. Symp. Aqua Bio-mechanisms: 51-56.

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4. Hove, J.R., L.M. O'Bryan, M.S. Gordon, P.W. Webb, and D. Weihs. (2001) Boxfishes (Teleostei: Ostraciidae) as a model system for fishes swimming with many fins: Kinematics. J. Exp. Biol. 204: 1459-1471.
5. Bartol, I.K., M.S. Gordon, M. Gharib, J.R. Hove, P.W. Webb, and D. Weihs. (2002) Flow patterns around the carapaces of rigid-bodied, multi-propulsor boxfishes (Teleostei: Ostraciidae). Integr. Comp. Biol. 42: (in review).
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7. Hove, J.R., M.S. Gordon, L. O'Bryan, P.W. Webb, and D. Weihs. (2003) A comparison of swimming energetic costs in two tropical fish species. J. Exp. Biol. (in preparation).

Video research reports:

1. Gordon, M.S. (1999) Boxfishes: natural autonomous Underwater vehicles. 7 min. length, sound, color, VHS.
2. Gordon, M.S. and M. Gharib. (2001) Hydrodynamics of swimming in boxfishes. 10 min. length, sound, color, VHS.

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2. Hove, J.R. and M.S. Gordon. (1997) Energetics of Swimming in the spotted boxfish (Ostracion meleagris. Amer. Zoologist 37: 107A.
3. Gordon, M.S., J. Hove, L. O'Bryan, P.W. Webb, and D. Weihs. (1997) Fishes swimming with many fins: boxfish as a model system. Amer. Zoologist 37: 188A.
4. Bartol, I.K. and M.S. Gordon. (2000) Flow patterns around boxfishes: role of body keels in dynamic stability. Amer. Zoologist 40:937.
5. Bartol, I.K., M.S. Gordon, M. Gharib, D. Weihs, and P.W.Webb. (2001) Vortical flows around rigid-bodied, multi-propulsor swimmers. Amer. Zoologist 41: 1386.